

DESIGN AND DEVELOPMENT OF 3D PRINTED BIODEGRADABLE PULMONARY STENT

Submitted in partial fulfilment of the requirements for the award of
Bachelor of Technology degree in Biomedical Engineering.

By

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**DEPARTMENT OF BIOMEDICAL ENGINEERING
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SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

**Accredited with Grade "A" by NAAC | 12B Status by UGC | Approved by AICTE
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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **Pruthula Pandalaneni (37240056), Sofica B (37240080)** who have done the project work as a team who carried out the project entitled "**Design and Development of 3D Printed Biodegradable Pulmonary Stent**" under my supervision from **October 2020 to March 2021**

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DECLARATION

We, **Sofica B (37240080)** and **Pruthula Pandalaneni (37240056)** hereby declare that the Project Report entitled **Design and Development of 3D Printed Biodegradable Pulmonary Stent** done by us under the guidance of **Dr. J. Prem Kumar**, Department of Biomedical Engineering at **MedCuore Medical Solutions Private Limited, Old Washermanpet** is submitted in partial fulfilment of the requirements for the award of Bachelor of Technology degree in Biomedical Engineering.

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ABSTRACT

Pulmonary disease is a significant health-care and economic burden across the world. Pulmonary stents have been proven as an effective treatment device for tracheobronchial diseases such as tracheomalacia, malignant and benign neoplasm and endothelialisation. There are numerous studies on the design of airway stents and many significant manufacturing methods have been reported in the past decades. However, in terms of design, modelling, and production, there is no systematic framework for pulmonary stent product creation. One of the major enduring challenges to the use of airway stent includes a selection of stent size. Critical oversizing or undersizing of stent often results in incomplete stent apposition or under expansion. After drug-eluting stent implantation, final stent expansion often fails to reach desired stent specifications, and suboptimal stent expansion can lead to an adverse clinical event. 3D printing materials, tools, processes, and techniques have progressed to the point that on-demand, highly personalized patient treatments are now possible. This study aims to highlight the importance of customized stent with 3D printing technique based on fused deposition modelling that has an exact geometric of the patient airway structure to minimize the probability of irregular stent size and rejection. The exact dimensions of a patient's airway structure are obtained using standard imaging techniques available at hospitals and a stent is then printed on-site to precisely fit the tracheobronchial dimensions. The inspiration for this novel 3D-printing technique was to develop a way to realize not "one size fits all". This project emphasizes the importance of Additive manufacturing along with design and material characteristics.

Keywords

Pulmonary stent, Geometric constraints, 3D printing, customized patient treatments, imaging techniques

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LIST OF ABBRIVATIONS

PLA	POLYLACTIC ACID
3D	THREE DIMENSIONAL
COPD	CHRONIC OBSTRUCTIVE PULMONARY DISEASE
CT	COMPUTED TOMOGRAPHY
MRI	MAGNETIC RESONANCE IMAGING
FDM	FUSED DEPOSITION MODELLING
CAGR	COMPOUND ANNUAL GROWTH RATE
STL	STANDARD TESSELLATION LANGUAGE

CHAPTER 1

INTRODUCTION

Pulmonary disease is highly prevalent, affecting millions global death annually. Pulmonary disease is a class of diseases that involves the lung and airway structure. Pulmonary disease includes COPD, asthma, lung cancer, etc. In both men and women, lung cancer (both small cell and non-small cell) is the second most common cancer. Lung cancer is by far the most common cause of cancer death in both men and women, accounting for about 25% of all cancer deaths. An airway stent is a multi-material endobronchial prosthesis that protects and retains the hollow tubular airway structure's patency. An airway stent can help prevent a tumour from spreading into the airway, heal or control airway fistulas, and protect the airway wall against collapse or external compression. ^[22]

Therefore, the Selection of stent size relative to the target airway structure is considered as important as a post-deployment optimization strategy. Laser micro-cutting is the standard production technique in the stent industry. Three-dimensional (3D) printing, a technique used in the biomedical industry, has recently emerged as a viable option for producing biomaterials. The 3D printing system, applied to rapid prototyping in structural fabrication can easily manufacture biomaterials, such as BRS, better than other devices. 3-dimensional printing biodegradable pulmonary stent technology has obvious advantages over traditional processing technology. 3-dimensional printing technology is an additive manufacturing technology that can control the distribution of materials, reduce product development costs, and shorten product development cycles. As a result, using 3D printing technology based on fused deposition modelling (FDM) to conduct digital design and manufacturing research on biodegradable polymer is important. The aim of this study is to create a product development approach for pulmonary stents that focuses on design, simulation, and manufacturing. The methodology brings together insights from numerous engineering design disciplines to make pulmonary stent development more flexible and more cost-efficient. ^[16]

1.1 PULMONARY STENT

An airway stent is a multi-material endobronchial prosthesis that protects and retains the hollow tubular airway structure's patency. An airway stent may impede extension of a tumour into the airway, may help in the healing or management of airway fistulas.

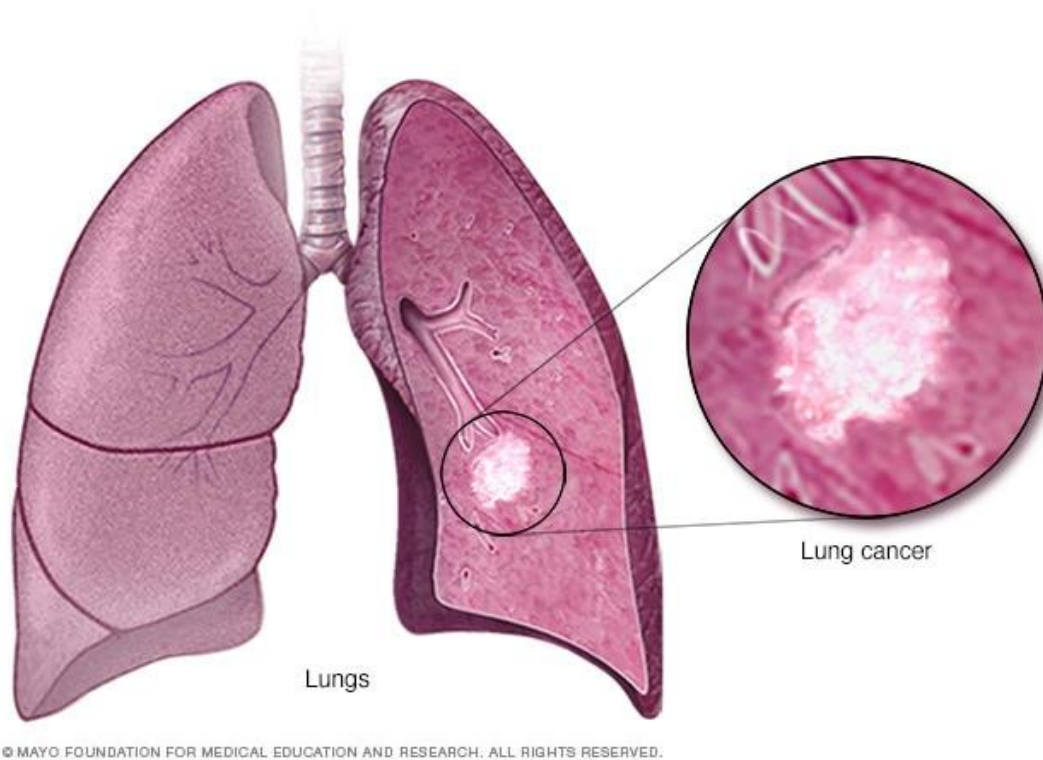


Figure 1.1 Lung with tumour

By improving their design, structure, and component materials, new pulmonary stent technology continues to strive to improve on the outcomes of previous generations of devices. New generations of drug-eluting stents, non-polymeric stents, bioresorbable polymer-coated stents, and completely bioresorbable scaffolds are among these innovations.^[3]

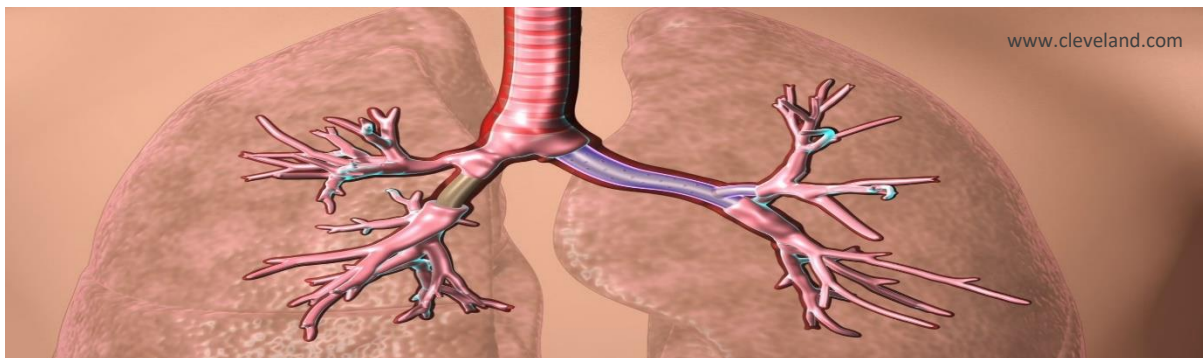


Figure 1.2 Pulmonary stent inside an airway structure

Desirable stent characteristics

- Low crossing profile
- High flexibility
- Radio-opaque
- Thromboresistant
- High stent/host compatibility
- High radial strength
- Low metallic surface
- Favourable radiographic properties
- Circumferential coverage
- Good tractability
- Easy Development ^[23]

1.2 EVOLUTION OF STENT

The term stent derives from a dental prosthesis developed by the London dentist Charles Stent (1807-1885), indicate any device used for extending stretching or fixing in an expanded state. Ulrich Siegart, Jacques Puel, and colleagues implanted the first stent in human pulmonary arteries in 1986, by using Wall's's stent sheathed self-expanding metallic mesh scaffold in the peripheral and pulmonary arteries of eight patients. It was a self-expanding stent consisting of 20 strands with diameters ranging about 0.06 to 0.09 mm, arranged in a self-expanding mesh design. It was flexible; its length ranging from 15 to 30 mm; and its diameter between 3.0 to 6.0 mm. The "Wall" stent, which is made of bare metal and self-expands, was able to provide a scaffold that avoided acute vessel closure and late constrictive recoil. A phase 2 study evaluating the Gianturco Roubin stent to reverse plain old balloon angioplasty in acute or threatened vessel closure was started in 1988, which ultimately leading FDA approval for this indication was granted by the United States Food and Drug Administration in June 1993. Julio Palmaz stent devised a balloon-expandable slotted stainless stent with rectangular diamond-shaped slots is the mother of all the modern stents The Gianturco Roubin stent¹⁰ (approved in the United States in 1993) had a poor radial strength, which was responsible for an increased rate of restenosis and stent thrombosis. Later, Medtronic proposed a coil stent or Wiktor stent. The field has

continually evolved, since the first pulmonary angioplasty was performed to relieve angina in a human.

Early BMS were self- or balloon expandable and were made of 316 L stainless steel, nitinol wire coils, or nitinol coils with different designs. Unfortunately, bare-metal stents (BMS) have been linked to excessive neointimal formation as a response to procedure-related wound healing in up to 30%–40% of cases, identical to plain old balloon angioplasty.^[33]

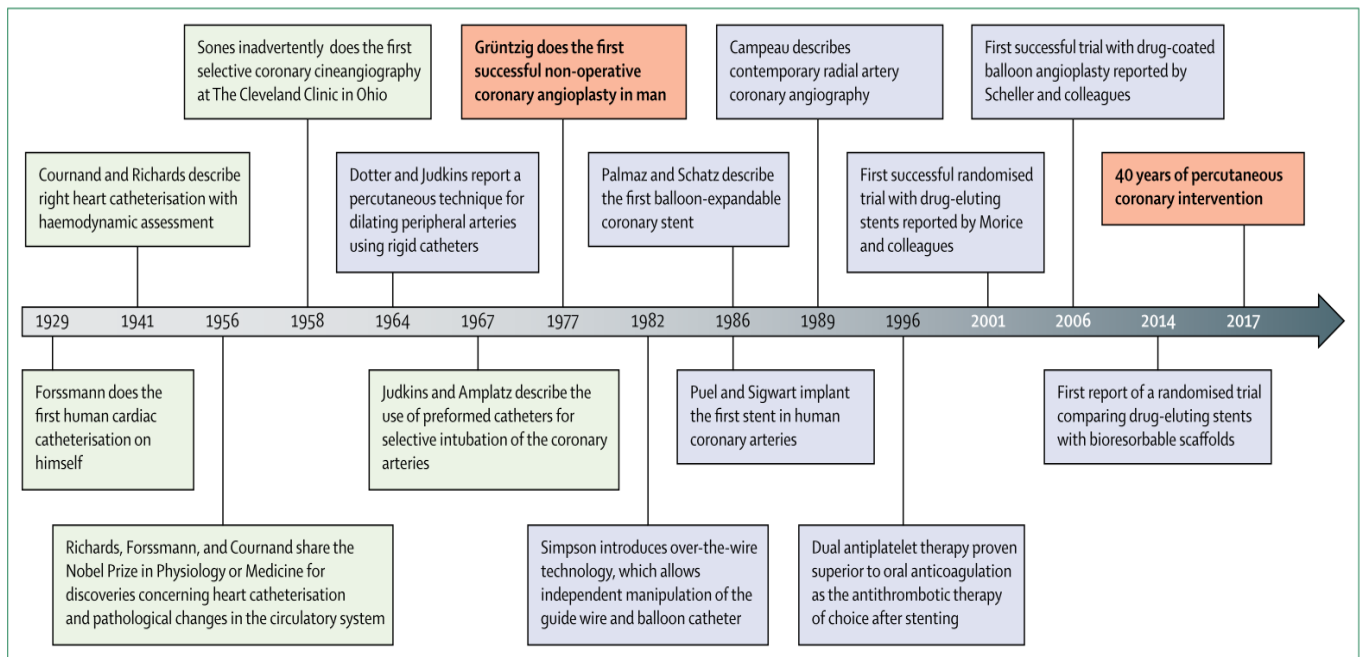


Figure 1.3: Evolution of stent

1.3 PULMONARY STENT MARKET SIZE AND SHARE

Rising prevalence of pulmonary diseases, such as lung cancer, along with the growing geriatric population at higher risk of these tracheobronchial diseases is expected to propel the demand for airway stents over the forecast period.

The lung stent market is expected to rise at a CAGR of 6.7 percent from USD 87 million in 2019 to USD 120 million in 2024. The global increase in the prevalence of lung cancer and chronic respiratory diseases, as well as the growing preference for minimally invasive procedures, are all contributing to the market's growth. However, the associated complications of using these stents, as well as an increase in the availability of alternative treatments, could limit the market's growth. ^[17]

Attractive Opportunities in the Airway Stent/Lung Stent Market



Figure 1.4: Airway stent market share

1.4 IMPORTANCE OF A STENT

Pulmonary stent material engages in an important role in the clinical performance because of the mechanical support offered to the airway structure and compatibility of the material to the airway structure. Thus, material, configuration, design, and manufacturing method play an important role in proper functioning of the stent. ^[24]

1.5 TECHNOLOGICAL TRENDS AND CHALLENGES

Despite many advancements in stent development, numerous studies are continued to show high efficacy, long term safety, and clinical outcomes in medical studies. Stents are classified by their mechanism of expansion, construction, and coatings. The key segmentation of stent market is by stent type, deployment, manufacturing process, end user and other aspects.

The Major challenges is the influence of airway structure size on long-term clinical and outcome after pulmonary stent placement. Once ill-fitting stents move within the airway structure, they will ultimately fail. In these cases, physicians must somehow re-open the blocked stent. It's an expensive and risky process. Geometric constraints within the patient's airway structure, such as a significant curvature that can disturb airflow, inflicting ancient stents to fail. Hence by printing a stent that has the exact geometric

and biologic requirements of the patient's airway structure, we expect to minimize the probability of these complications.

Apart from the design aspects, manufacturing methods also play vital role as they face stent efficacy challenges. Precision manufacturing techniques such as laser machining, photochemical etching, electro-discharge machining, water jet, braiding, vapor deposition, etc., are considered necessary to manufacture the stents. Proper surface treatment techniques must be carried out to remove burrs and oxidation layers. ^[6]

CHAPTER 2

LITERATURE SURVEY

2.1 STENTS FOR DIFFERENT APPLICATIONS

Stents vary in size and material supported their supposed use. Although wire mesh viscus stents ingrained into arteries are the foremost common technology that comes to mind, the essential construct of stenting may be employed in many alternative organ Stents are merely tube that keep a passageway open, and therefore the form contains several non-cardiac passageways

Biliary (Bile duct) Stents

Endoscopic biliary stenting is a procedure to open your blocked biliary duct (tube). A stent is placed in your blocked bile duct during the procedure. A stent is a small plastic or metal tube used to keep your bile duct open. Biliary stents are marketed in diameters ranging from 5 to 12 Fr and lengths ranging from 1 cm to >15 cm. [7]



Figure 2.1: Representation of Biliary stent

Ureter Stents

Ureter stents help to open up the urethra, the ducts between the kidneys and the bladder. Ureteral stents are made of polymers (plastic) and are versatile. A stent is a thin hollow plastic tube that is used to keep your ureter open and allow urine to flow.

Stenting may be used for the short or long term (up to 3 months) depending on the patient's needs.

The length of stents used in adult patients ranges from 24 to 30 cm. In addition, stents come in different diameters or gauges to fit different sizes of ureters. Usually, the stent is inserted with the help of a cystoscope. ^[18]



Figure 2.2: Ureteral Stent

Oesophageal Stents

Oesophageal stents are a widely used treatment method for various oesophageal pathologies such as malignant and benign obstruction and oesophageal perforation. In an oesophageal stent procedure, a tube is placed in your oesophagus (throat) to keep the area blocked open. The tube helps you swallow liquids and solids. Stent sizing options, including a length of 60mm and a diameter of 14mm, designed to meet a variety of clinical needs. ^[25]



Figure 2.3: Oesophageal stent

Colorectal Stents

Colorectal stents are used to treat large bowel luminal obstruction caused by cancer. The use of colonic stents has changed dramatically in recent years. Emergency colonic surgery is commonly associated with a high rate of mortality, morbidity, and stoma development. Colonic obstructions can be relieved using colonic stents. [26]

Cerebral stent

A cerebral stent opens a clogged or blocked artery in the brain to promote the circulation of blood. The principle behind is the prevention of strokes by ensuring the brain's blood supply is not compromised. [26]

2.2 TYPES OF STENT MANUFACTURED

- Bioengineered stent
- Bare metal stent (BMS)
- Drug eluting stent (the second revolution in stenting)
- Bioresorbable stent

2.3 MANUFACTURING PROCESS OF A STENT

Stents are manufactured from several forms of materials such as machining from tubular Laser cut with water jet forms, machining on the sheet, and later, the ends are attached by welding, rolling, etc., to form into a tubular form. Stents are manufactured in a number of methods and are classified according to traditional and modern methods of production. The manufacturing process depends mainly on the materials and the type of stent chosen. [27]

Manufacturing process=f (material, stent type)

2.3.1 LASER MACHINING

Laser cutting is the most widely used manufacturing method in the medical device industry due to its precision machining process. The high energy density laser beam is concentrated on the surface of the workpiece; the thermal energy is absorbed, which heats and transforms the workpiece volume into a molten, vaporised or chemically modified state that can be easily removed by high pressure flow aiding the gas jet.

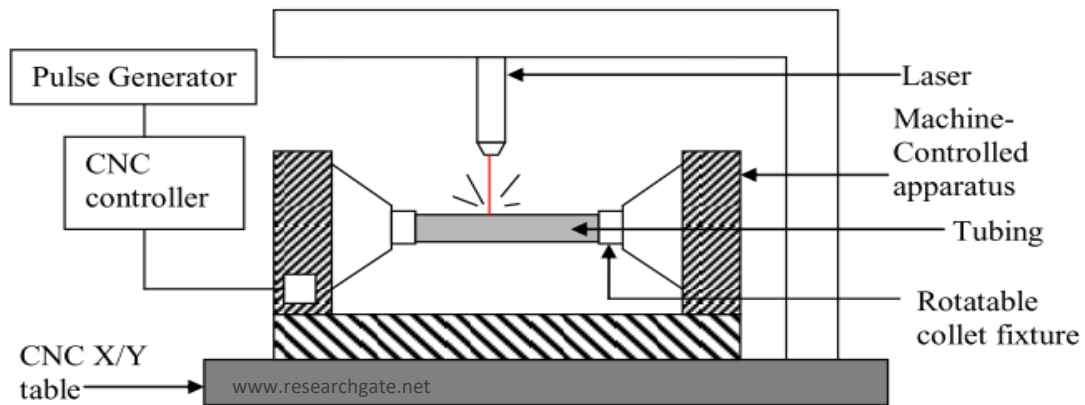


Figure 2.4 Laser beam cutting machine

Laser cutting is a thermal process that results in thermal damage such as heat-affected area, striation, recast layer, microcracks, residual tensile stress, and dross. In order to overcome thermal damage, basically the following post-processing techniques are used: pickling techniques, soft etching, annealing and electro-polishing. Several studies have looked at how process parameters influence efficiency, as well as how to reduce thermal issues and thus lower stent production costs. [8]

2.3.2 ELECTRIC DISCHARGE MACINING

The Electric Discharge Machinery is a mechanism in which electrical energy is used to produce the Spark between the instrument and the workpiece submerged under the dielectric medium, causing the material to be separated from the workpiece's surface by local melting or vaporisation. [8]

2.3.3 HYDRO CUTTING

The method introduces a jet stream with a high water intensity on the surface of the material to cut the material into slots. In the hydro cutting process, the material is exposed to jet streams with abrasives, such as granite, to form slots. In addition to abrasives, hot water with chemical applications also promotes the cutting process. [8]

2.3.4 PHOTSENSITIVE CHEMICAL ETCHING

The method of etching is based on the process of photolithography. In this process, the desired mask pattern is first projected onto a plain sheet coated with photoresist, which can be developed and etched to the desired pattern after exposure. UV rays from the light source expose the workpiece and provide photosensitive resistance coat

on the material to react and change the properties of the exposed areas on the workpiece. The work piece with stands electrochemical etching in order to form a stent structure. [8]

2.3.5 CASTING

This is another technique in which the stent can also be formed by subjecting one or more of them. The metal can be directly coated in a stent-like manner, or it can be cast into sheets or tubes from which the innovative stents are made. There are several methods of casting and they are centrifugal casting, pouring the stent material in the indentations/ grooves. [8]

2.3.6 VAPOUR DEPOSITION

Vapour deposition, also known as evaporation, is the method of heating precursor powders in a high-vacuum atmosphere until the vapour pressure is high enough to cover a substrate suspended above the evaporation source.

The set-up assigns the mandrel to the rotary motor and rotates in the direction of the vector at a speed of 1-60 rpm. Vacuum fills the chamber and creates an appropriate vacuum pressure. The source material flows from the top of the chamber to the mandrel. The completion of the process takes place when the desired thickness of the material deposits is placed on the mandrel. [8]

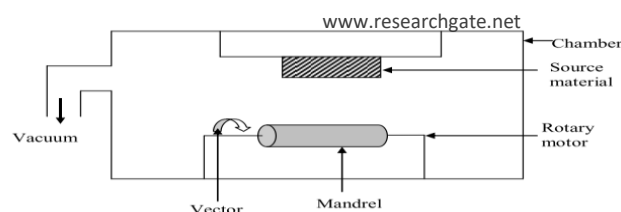


Figure 2.5: Vacuum deposition by evaporation

2.3.7 WIRE BRAIDING

The break mechanism connects the wire spool and inactivates any time the wire is inessential. The feed rate of the yarn and the wire to the weave is 4:1. The materials employed for yarns are natural fabric, polyester, polypropylene, polyethylene and for wire are metal alloys. [8]

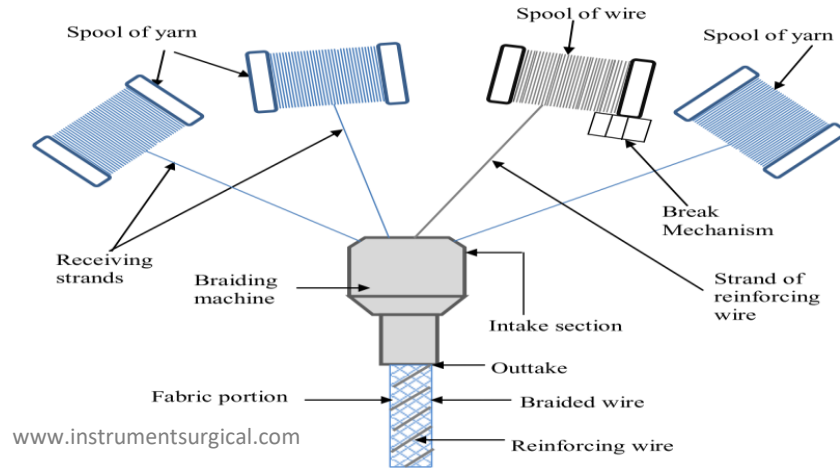


Figure 2.6: Braiding machine with yarn and wire to form tubular stent

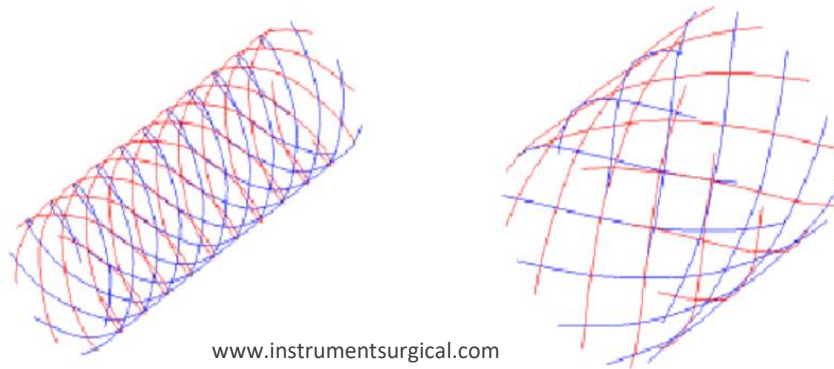


Figure 2.7: Single wire braided wire stent

2.3.8 ELECTRO FOAMING

Electroplating is performed on the mandrel in each pattern of this process. When the desired thickness is reached, the mandrel is etched away from the electro-formed stent, leaving a free-standing structure with a fully functional stent. [8]

2.4 TYPES OF MATERIALS USED FOR MAKING A STENT

Stent materials are selected on the basis of mechanical properties, bio functionality, biocompatibility (i.e., corrosion-resistant, less toxic, non-inflammatory and thrombo-resistant) and biological inertness. These materials are divided into metals, metal alloys, polymers and ceramics.

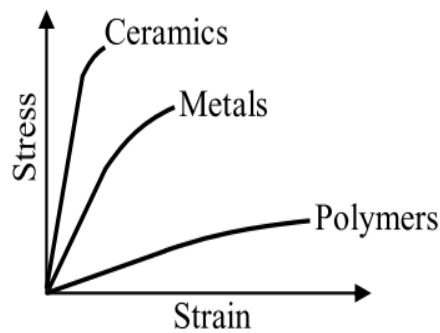


Figure 2.8: Properties of ceramics, metals, and polymers

Metals

Stents are used to dilate vessels in the bile duct, the oesophagus, and other passages. Because of their mechanical properties and visibility on X-ray imaging, metals are the most commonly used materials for stents. Passages for dilation. Therefore, elasticity or plasticity for Metals have a high elastic modulus due to high tensile strength, leading to low stresses in the material. Thus, metals such as iron, titanium, tantalum, cobalt, chromium, magnesium, nickel, iron, zinc, stainless steels 304L, 304V, 316LV; mild steels, Ni-Cr-Fe alloys, platinum enriched stainless steels, and tungsten alloys are biocompatible and are considered as biomaterials. The materials such as stainless steel, nitinol (Ni-Ti), cobalt-chromium (Co-Cr) are corrosion resistant metal alloys. Iron and magnesium are considered as fewer toxic metals and little amounts of calcium, zinc, and manganese alloys show beneficial properties.^[20]

Table 2.1: Stent metals and their properties

METALS	PROPERTIES	ALLOYS
Stainless steel	Passivation, Corrosion resistance	316 L
Nitinol	Self-expanding, Super elastic, Good MRI	
Titanium	Passivation, Less ductile, corrosion	
Tantalum	Passivation, Highly ductile, Corrosion resistance	
Nickel	Highly toxic, Inflammatory	
Chromium	Highly toxic, Inflammatory	Co-Cr
Magnesium	Biodegradable, less toxic, immediate degradation, less ductile	MgLi

Gold	Radio opaque
Niobium	Passivation
Zirconium	Passivation

New techniques for treatments using metallic stents are continuously being developed, and such development will continue into the foreseeable future. [20]

Polymers

Polymers are used as stent materials as they have viscoelastic properties. In the past, synthetic polymers, such as poly (ethylene) (PE), polyurethanes (PUR), poly (glycolide) PGA) and polylactides (PLA) were the material of choice for implants and other medical devices. While PURs are well established as scaffold materials for airway structure grafts due to their excellent hemocompatibility, PGA is commonly used as suture material for different surgical applications. Further, PGA-containing scaffolds blended with poly (ϵ -caprolactone) (PCL) are used for PGA-based drug delivery systems. [20]

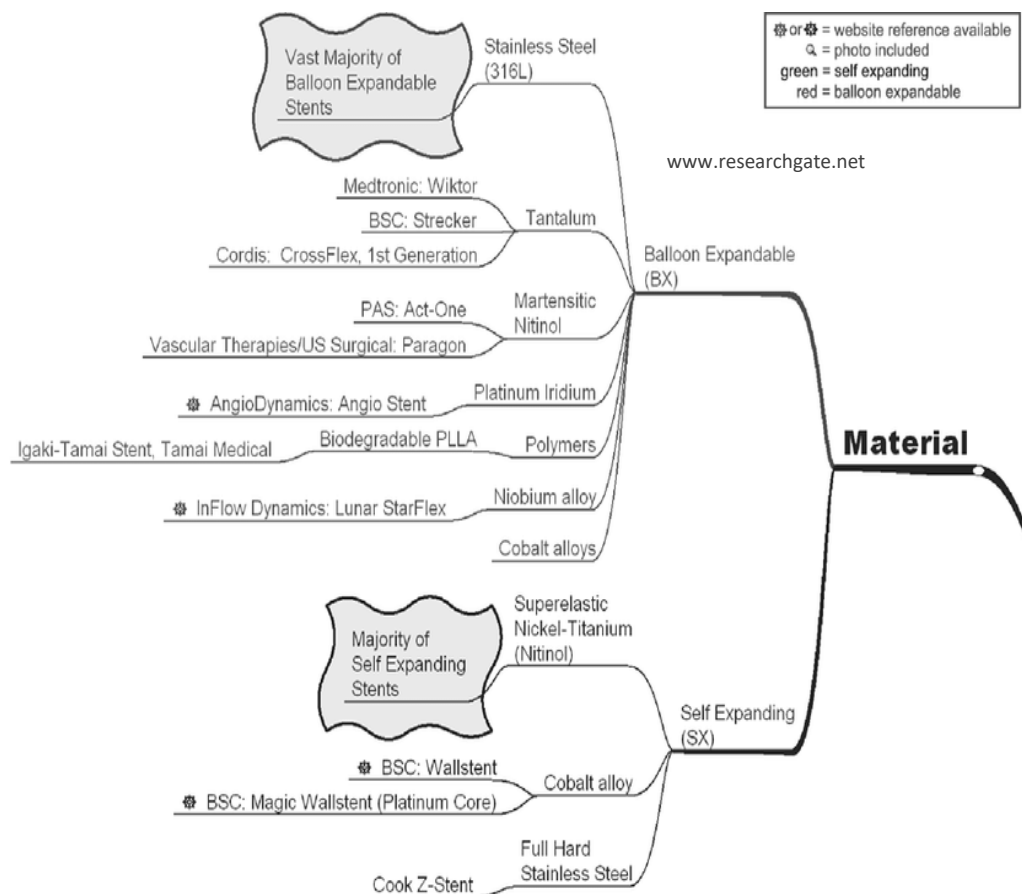


Figure 2.9: Overview of materials used in stent

2.5 TYPES OF STENT DESIGNS

Coil

Coil stents are characterised by metal wires or strips formed in the shape of a circular coil. The coiled stents of the members are arranged substantially perpendicular to the long axis and are therefore more flexible. The design of the coil had a larger strut width with gaps and fewer or no connections between struts. The width of the strut is greater; there is a gap between the struts, and there are no connections between the struts that give it more flexibility. However, the design lacks radial strength, and the wide gap allows tissues to dangle. As a result, the design of the coil has become obsolete and replaces the design of the tube with the higher radial strength. ^[9]



Figure 2.10: Coil stent fabricated from nitinol ribbon

Helical spiral

In general, helical spiral designs are promoted because of their flexibility. They are very flexible with no or minimal internal connection points, but they also lack longitudinal support. As such, they may be subject to elongation or compression during delivery and deployment and, as a result, to irregular cell size. With internal connecting points, some flexibility is sacrificed in exchange for longitudinal stability and additional cell size control. ^[9]



Figure 2.11: Minimally connected helical spiral geometry.

Woven

This category includes a variety of designs made of one or more wire strands. It provides excellent coverage; it is typically significantly shortened during expansion. The radial strength of such a woven structure is also very dependent on the axial fixation of its ends. ^[9]

Individual rings

Single 'Z' rings are commonly used to support grafts or similar prostheses; they can be individually sutured or otherwise attached to the graft material during manufacturing. Typically, these structures are not used as airway structure stents on their own. ^[9]

Sequential rings

Stents in this group are made up of a set of expandable Z-shaped structural elements (known as struts) that are linked by connecting elements (known as bridges, hinges, or nodes). This type of construction accounts for most commercially available stents. ^[9]

CHAPTER 3

AIM AND SCOPE

3.1 AIM

To create a product development approach for a pulmonary stent that focuses on design, simulation, and manufacturing. The 3D printing methodology brings together insights from numerous engineering design disciplines to make pulmonary stent development more flexible, customized, cost-efficient and reduced manufacturing time.

Chapter – 4

MATERIALS AND METHODS

There is a significant number of developments in order to achieve the ideal stent design. One of the problems with current stents is that they have standard lengths. As mentioned above, the longer the stent, the more likely it is to be broken.

4.1 3D PRINTING – A PROMISING MANUFACTURING PROCESS OF A STENT

Recently, 3D printing, a specific biomedical technique, has emerged as an alternative system for the production of biomaterials. 3D Printing Technology (3D Printing) is an additive manufacturing technology that can control the distribution of materials, reduce the cost of product development and reduce product development. Therefore, relying on 3D printing technology, it is very important to carry out digital design and research into biodegradable polymer stents. The 3D printing system, when used for rapid prototyping in structural fabrication, is capable of producing biomaterials like BRS more efficiently than other systems.

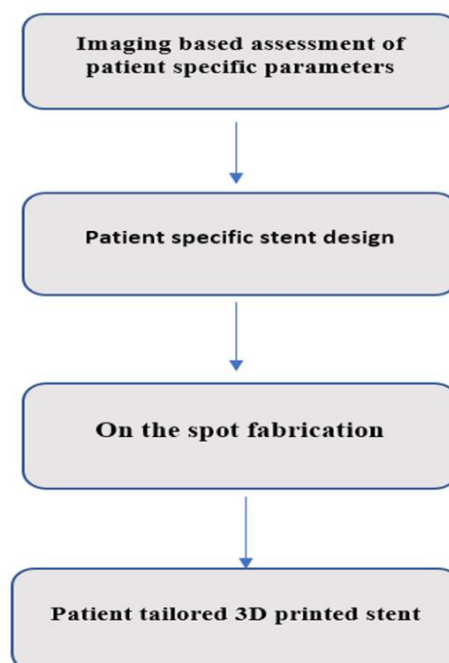


Figure 4.1: Flow of stent design

Clinicians use Computed Tomography (CT) technology to obtain 3D images for a complete and deep view of the anatomical region of interest to better understand any associated medical condition. However, CT is not the only technique working in the 3D domain, since several other approaches are possible, including 3D magnetic resonance (MRI), positron emission tomography (PET), 3D ultrasound and 3D laser scanning (external). The use of AM solutions for productions based on medical data obtained from specific patients enables the manufacture of unique, customised devices to respond to individual needs.^[4]

4.2 GEOMETRIC ASPECTS

The diameter of the stents, the form of the struts, the width, length, and thickness of the struts, and the width, length, and thickness of the struts are all used to classify the stents. Pulmonary stents usually have a length of 20-80 mm, a diameter of 8-20 mm, a width of 0,08-0,1 mm and a thickness of 0,07-0,14 mm. The geometry depends on the design of the stent and the length of the stent varies. Geometric designs/configurations (mesh structure, coil, slotted tube, and ring, multi-design). Stents are grouped into three categories based on their design: coil, tubular mesh, and slotted tube.

- Tubular mesh stents consist of wires that are wound together in a meshwork, forming a tube. There are two types of specification in the tubular tube, the slotted tube and the modular tube.
- The slotted tube stents are made of metal tubes from which the stent design is laser cut. The members of this type of stent are arranged mainly along the longitudinal axis and are inherently rigid along this axis. ^[10]

4.3 CONFIGURATION

Structures, rings, cells, crowns and connectors are the backbone of the stent. Strut: single element forming a larger structural entity (cells, rings, and crowns). Cell: a small but repeating stent system with two layers of rings and connectors that can be open or closed. Connectors: attach the adjacent rings and they may be straight or curved, or they may be direct welds linking the rings directly. Rings and crowns are made up of a cluster of cells linked by connectors (1 crown= 2 trunks). Orientation of stents (in-phase or out-of-phase) and connectors (offset peak-to-peak; mid-shaft; peak-to-peak-

out-of-phase; peak-to-valley-in-phase). The design and geometry of these components define the mechanical performance of the stent: radial support and expansion capacity are determined by the crowns and rings; the number of connectors is responsible for longitudinal stability, flexibility, deliverability, side branch access and longitudinal integrity. Stents with an open cell design and less connectors provide more versatility, as well as less arterial injury and neointimal reaction. [28]

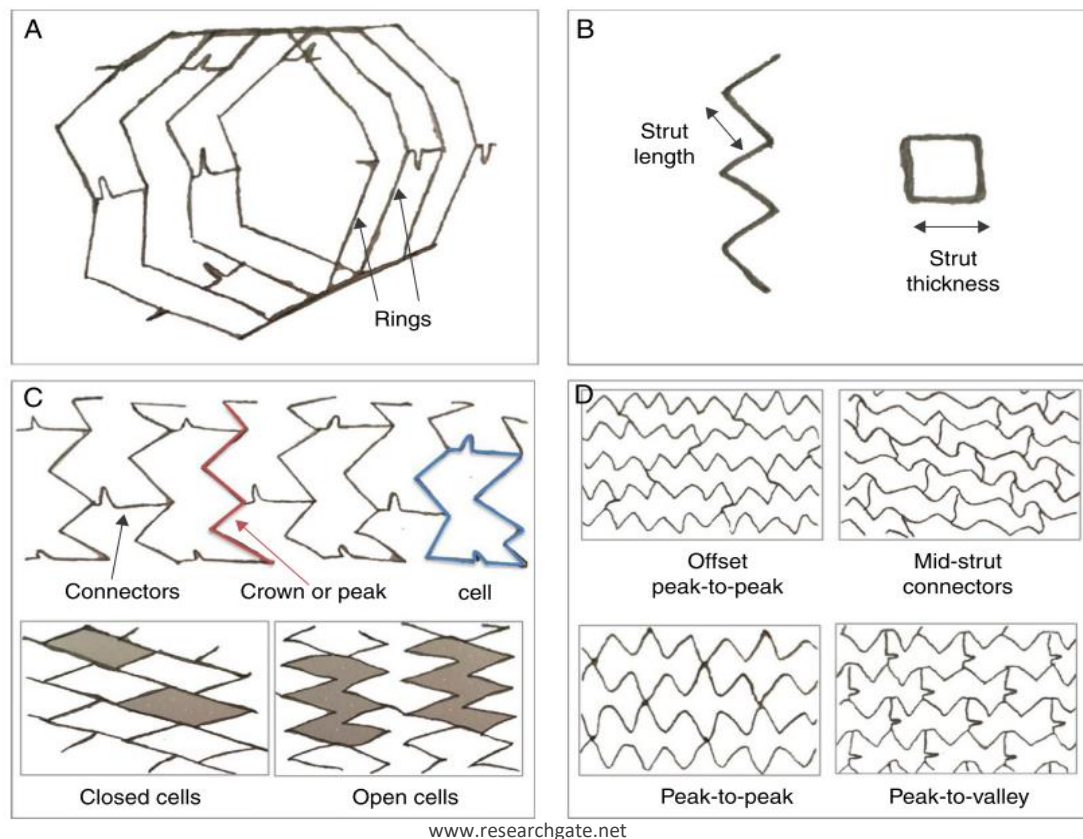


Figure 4.2: Structure and orientation of stent

4.3.1 OPEN CELL

- The bridging elements do not bind all or any of the internal inflection points of the structural components.
- Periodic peak-to-peak connections, peak-to-valley connections, and mid-step to mid-step connections. Unconnected structural components contribute to longitudinal flexibility.
- Stents with wide or open cells have been engineered to reduce the percentage of metal surface area and increase access to side branches. [19]

4.3.2 CLOSED CELL

- Sequential construction of the ring
- All internal inflection points of the structural members are interconnected by the bridging elements.
- Regular connections from peak to peak.
- Optimal scaffolding and a uniform surface, irrespective of the degree of bending.
- Less flexible than a similar open-cell design. ^[1]

Table 4.1: Stent design impacts drug delivery

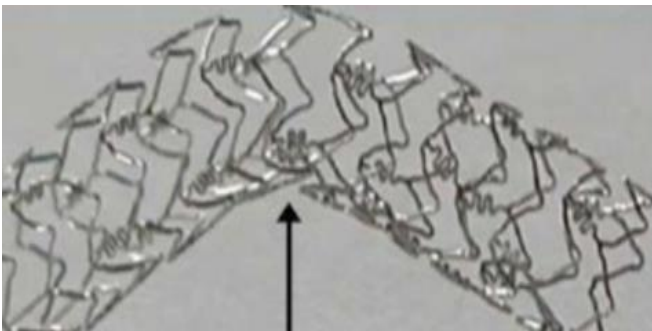
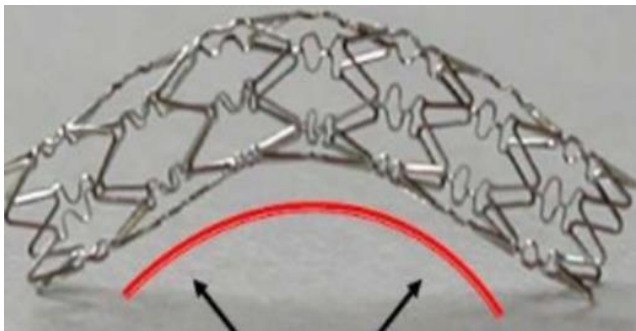
Open cell (Support segments are connected at 3 place)	Closed cell (Support segment are fully connected)
Gap-Low drug concentration  Pinch-High drug concentration	 More uniform drug concentration

Table 4.2: Properties of open and closed cell

Properties	OPEN CELL	CLOSED CELL
Radial strength	Low	High
Plaque Prolapse	High	Low
Metal: Airway ratio	Low	High
Conformability	High	Low
Side branch access	High	Low

4.4 RESEARCH SCOPE

The aspects of stent behaviour that are studied in research involve elastic recoil, foreshortening, longitudinal recoil, radial stiffness, coverage area, fracture mechanics, bending and flexibility. Stent materials also have a big impact on stent performance. The materials are selected based on mechanical properties, biocompatibility, and bio functionality. Biodegradability of stents is an important material aspect considered in current studies. Stents are expected to stay in the body for a period of 12-24 months and biodegrades after the airway structure is back to its normal position. The manufacturing process has an effect on how well stent's function. Surface finishing is a machining operation which is an important process after manufacturing stents. Material, design, manufacturing, clinical outcomes are some characteristics, the researchers investigate in the field of pulmonary stents. This study provides an overview of the existing stent types, their functionality, materials, and manufacturing conditions demonstrating the still huge potential for the development of promising stent solutions. ^[11]

CHAPTER 5

RESULTS, DISCUSSIONS AND PERFORMANCE ANALYSIS

5.1 MATERIAL USED FOR PRODUCTION

Polylactic Acid (PLA)

PLA has been used as a stent substantial in pulmonology due to its long track records of in-vivo biocompatibility.

Medical devices made of bioresorbable polymers are becoming increasingly popular in the medical and pharmaceutical fields. Typical representatives of biodegradable polymers are polyhydroxy carboxylic acids, such as PGA, PLA, poly (3-hydroxybutyrate) (P (3HB)), poly (4-hydroxybutyrate) (P (4HB)), and PCL. While P (4HB) is applicable for airway structure grafts and heart valves, P(3HB) has not been accepted for airway structure applications due to its capability to trigger extensive inflammatory responses in porcine models. The bio compatibility of these polymers, specifically in airway structure stenting, depends to a large extent on degradation kinetics.

Biomimetic polymers, such as phosphorylcholine (PC), poly (vinylidene fluoride) hexafluoropropylene (PVDF-HFP), and the BioLinx polymer, do not interfere with stent reendothelialization and are currently used in second-and third-generation DES.

Biodegradable polymers, such as PLA and poly (lactide-co-glycolide) (PLGA), have also been studied extensively to enhance their properties and biocompatibility.

To improve the functionality of stents, drugs are used as anti-thrombogenic, anti-proliferative, anti-inflammatory, anti-coagulants, or cholesterol-lowering agents. A few drugs used on the DES's are heparin, paclitaxel, sirolimus, zotarolimus and everolimus.

Polymer coatings aid in the reduction of thrombosis and neointimal hyperplasia rates. The loss of adhesion coating when crimping and unsheathing stents is a problem with polymer coatings.^[2]

Table 5.1: Biomaterials and its properties

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BIOMATERIAL AND ITS PROPERTIES

Properties	Materials				
	HA	PLA	PCL	TCP	Ti
Biocompatible	Yes	Yes	Yes	Yes	Yes
Biodegradable		Yes	Yes	Yes	
Bioactive	Yes				
Bioresorbable			Yes	Yes	
Bioinert					Yes

5.2 DESIGN OF CHOICE

Sequential rings

Sequential rings can be further refined by describing the way the structural elements are connected, and the nature of the resulting cells:

- Regular connection describes bridging elements that include connections to every inflection point around the circumference of a structural member.
- Periodic connection describes bridging elements that include connections to a subset of the inflection points around the circumference of a structural member. In a predetermined pattern, linked inflection points alternate with unconnected inflection points.
- 'Peak–peak connection' or 'peak–valley connection' are terms used to describe the locations at which the bridging elements join adjacent structural members. 'Peak–peak' bridging elements connect the outer radii of adjacent structural members, while 'peak–valley' bridging elements connect the outer radii to the inner radii of adjacent structural members. ^[12]

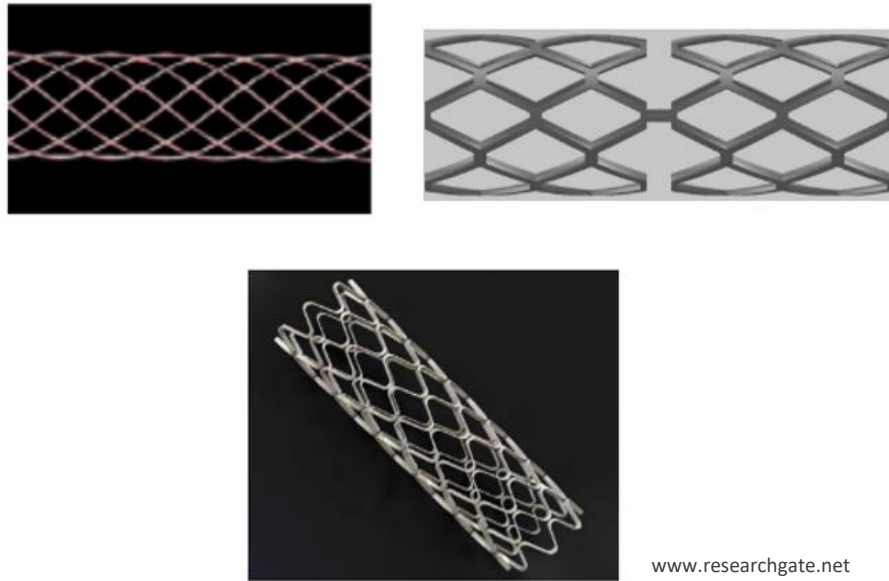


Figure 5.1: Sequential, Individual ring structure

5.3 3D PRINTING METHODOLOGY

Equipment

Stents were created using a 3D tubular printer and a 3D printing process. The FDM process is used in this 3D additive manufacturing machine.

FDM technology is easy to be used and capable to produce complex geometries. Despite these benefits, the layer-by-layer fabrication technique has a significant impact on this process and limits the level of surface finishing that can be achieved. As a result, one potential solution is to conduct post-processing on the components generated by FDM. These treatments can be mechanical and chemical.

The filament is melted into the extruder nozzle, which then deposits the melted material onto a controlled rotatory cartesian platform. The unit has a precision of 0.9375 mm on the X axis, 0.028125° on the W axis, 0.3125 mm on the Z axis, and 0.028125° in the 0.4 mm diameter extruder. [5]

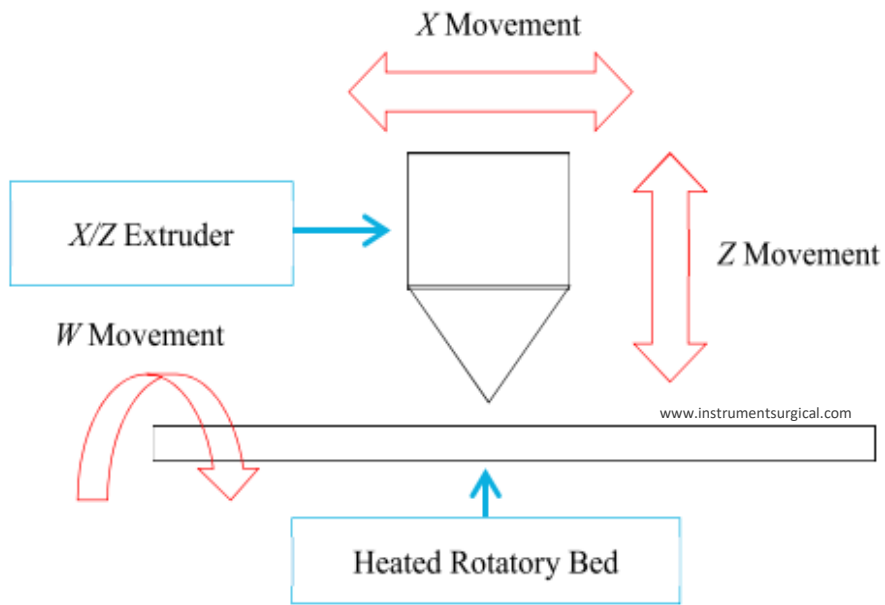


Figure 5.2: Machine methodology



Figure 5.3: 3D Printer (creality ender 3 plus)

Currently, there is a lot of research being conducted on how to adapt 3D printing research to a number of health-related applications.

5.4 DESIGNING AND TESTING SOFTWARE

The stent model used for the experiments was a hexagon and diamond-cells stent. The stent parameters were the following: inner diameter, stent thickness (ST), number of circumferential cells (NC), width and length of the cell (WC, LC), strut width (SW). These parameters determine the behaviour of the stent, the correct adjustment of them is crucial for calibrating the stent to the needs of each patient. [29]

Rhinoceros (typically called as rhino or rhino 3D) is a commercial 3D computer graphics. Rhinoceros geometry is based on the NURBS mathematical model and it focuses on creating mathematically precise representations of curves and freeform surfaces in computer graphics.

Through the 3D modelling software Rhino 3D to establish the two-dimensional plane of the stent to expand the 3D graphics, save the file as STL format.

- The saved design is imported into ANSYS software for simulation and checked for stent geometry, coordinate systems, connections, mesh, frictionless support, total deformation, penetration etc.
- Then the saved STL file is imported into the slicing software called ultimaker_cura 4.7.1, the path is generated, and then the generated path is exported from the slicing software and stored as the identifiable G-code of the pulmonary stent forming device.
- According to the influence of different 3D printing process parameters on the fabricating quality of the airway structure stent, the optimum parameters of the 3D printing moulding were determined, and the biodegradable polymer material PLA was used for printing. [30]

5.4.1 Design of experiments

- The filamentous PLA was selected as the scaffold moulding material, and the outlet diameter of the printing nozzle d was 0.4 mm. For the PLA stents, the temperature was 220 °C for

nozzle T^a , 25 °C for bed T^a , and a printing speed of 200 mm/min printing speed. [13]

Table 5.2: Geometry of stent

Structure	Geometry of nozzle (mm)	d(mm)	Strut thickness(mm)	L(mm)
Hexagon	0.4	20.0	0.3	80.0
Diamond	0.4	20.0	0.3	80.0

When comparing the bending versatility with stents of the same diameter, it is clear that stents with a longer connector and a narrower stent strut (t) width have an advantage; thus, stents with a loose geometric structure appear to be more flexible. Stents with a larger connector (h) and a moderate strut diameter are more favourable to a combination of bending flexibility and radial power, it can be deduced. [32]

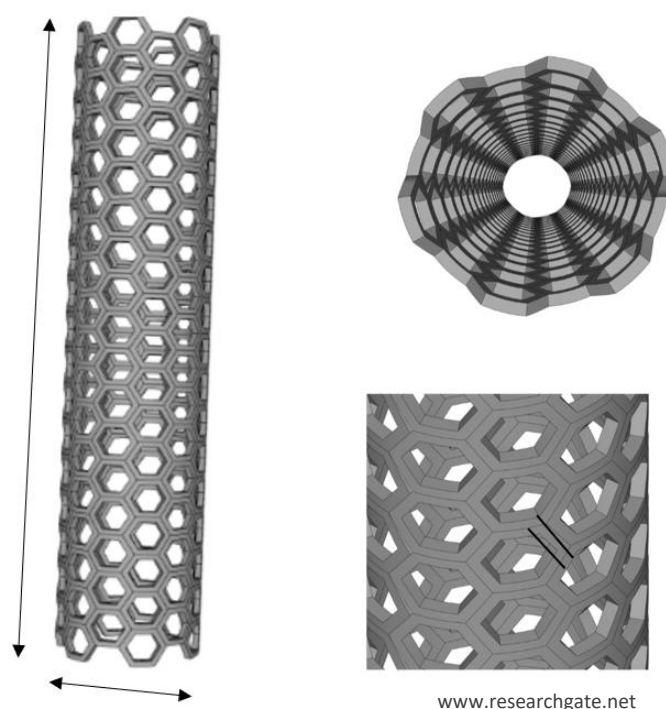


Figure 5.4: Design1 – View of CAD Stent design displayed in perspective view and top view

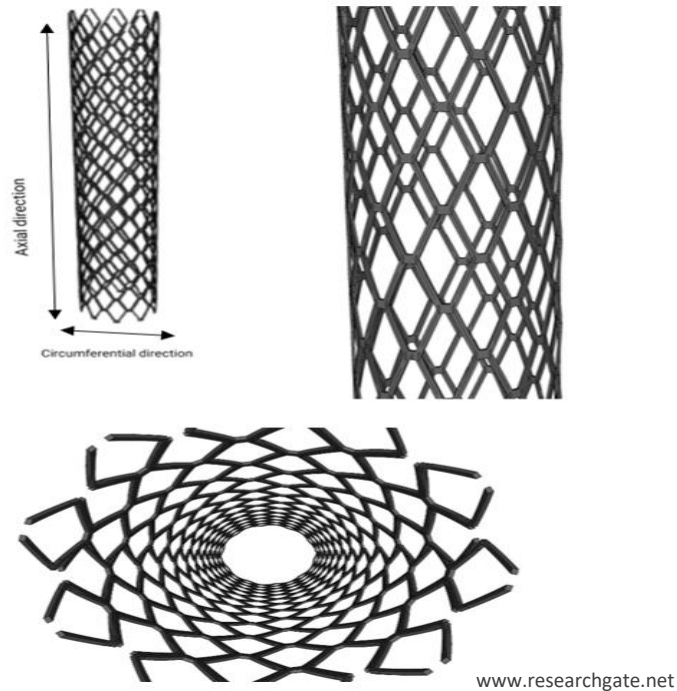


Figure 5.5: Design 2- Diamond shaped cell -perspective view

5.5 DESIGN REQUIREMENTS OF A PULMONARY STENT

Design plays a key role in stent performance. The design considerations for stents are high radial strength, low radial elasticity, good flexibility, low stent profile, good traction, minimal foreshortening, minimal longitudinal elasticity, and optimum scaffolding. Stents are manufactured with a nominal diameter and compressed to a smaller diameter to actuate through the passage to the lesion site and extended to the size of the nominal diameter (deployment). Some of the characteristics of the stents to be considered during design and simulation include the outer diameter, inner diameter, strut thickness, strut width, strut length, number of struts, length, metal to artery ratio, foreshortening, coiling and dog boning ^[31]

- Flexibility-The ability of the stent to pass inside the artery through the lesion area
- Radial stiffness-The support provided by the stent to the airway wall after the deployment of stent
- Longitudinal recoil- The ability of the stent to shorten after deployment and removal of balloon catheter

- Foreshortening-The ability of the stent to deform longitudinally after deployment.
- Radial recoil-The ability of stent to contract after the bronchoscopy is removed.
- Dog boning- The design characteristic to prevent restenosis caused by mechanical Stress.
- Coverage area-The area between the arterial wall and stent
- Target life-The fatigue durability to undergo cycling loads.

Considering all the above characteristics, the design plays a significant role in stent's performance [14]

5.6: FINAL DESIGNS

5.6.1: DESIGN 1

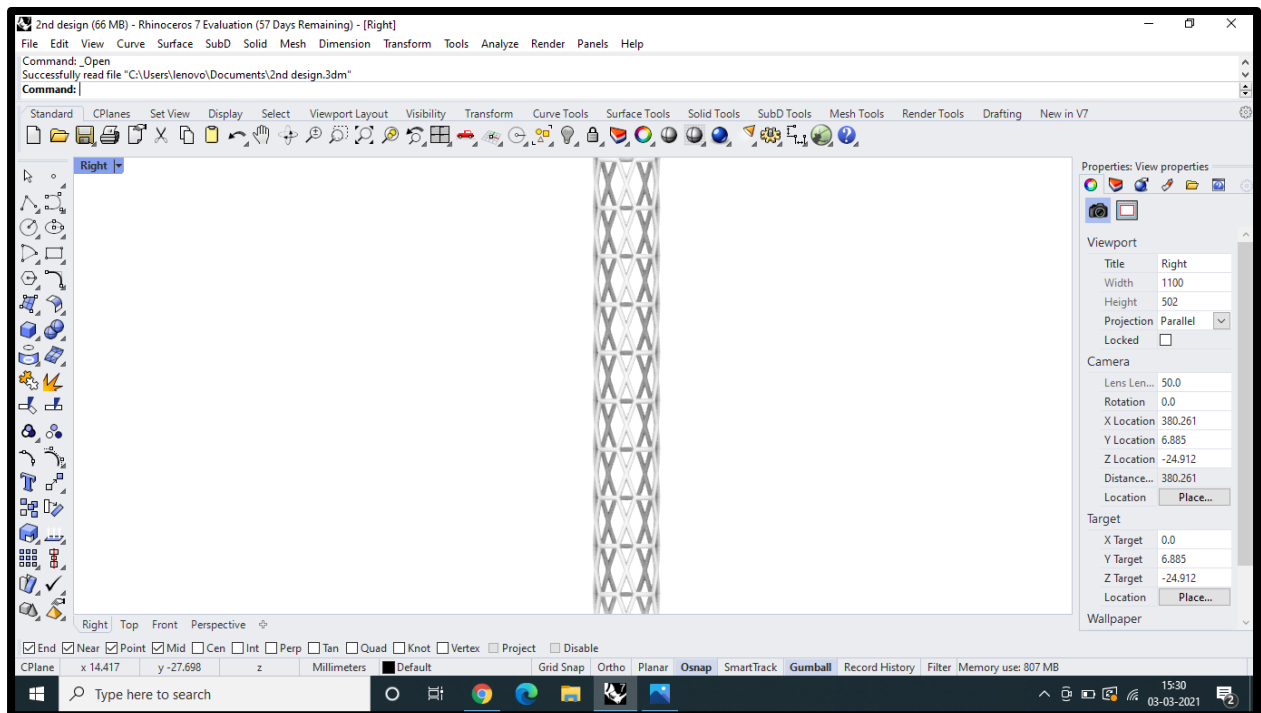


Figure 5.6: Design 1 - Pulmonary stent design displayed in perspective view

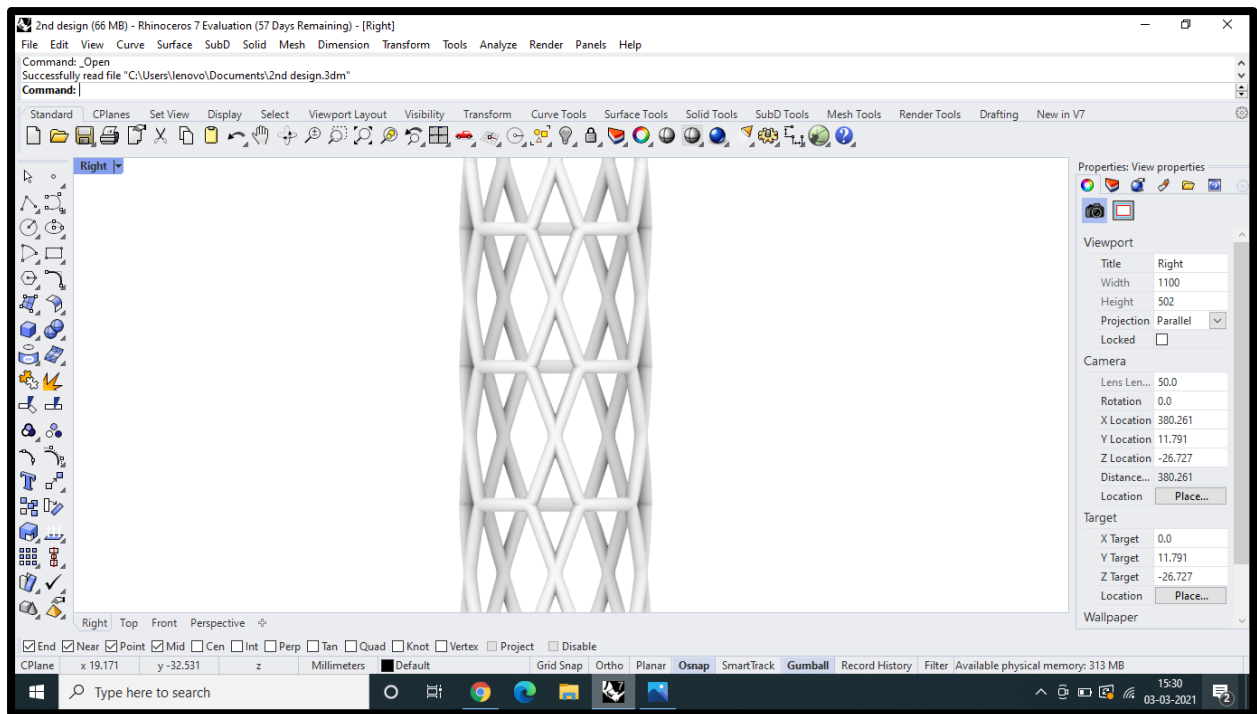


Figure 5.7: Design 1 – Struts of the pulmonary stent in perspective view

5.6.2 DESIGN 2

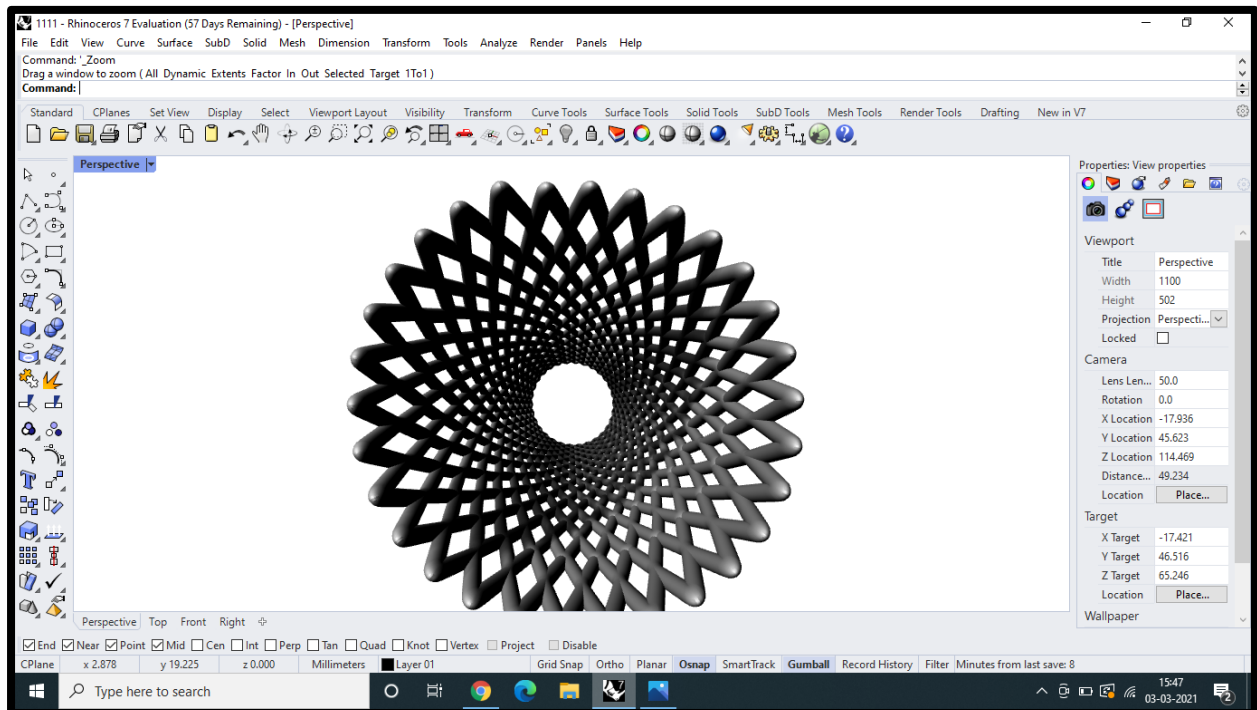


Figure 5.8: Design 2- Diamond shaped cell -top view

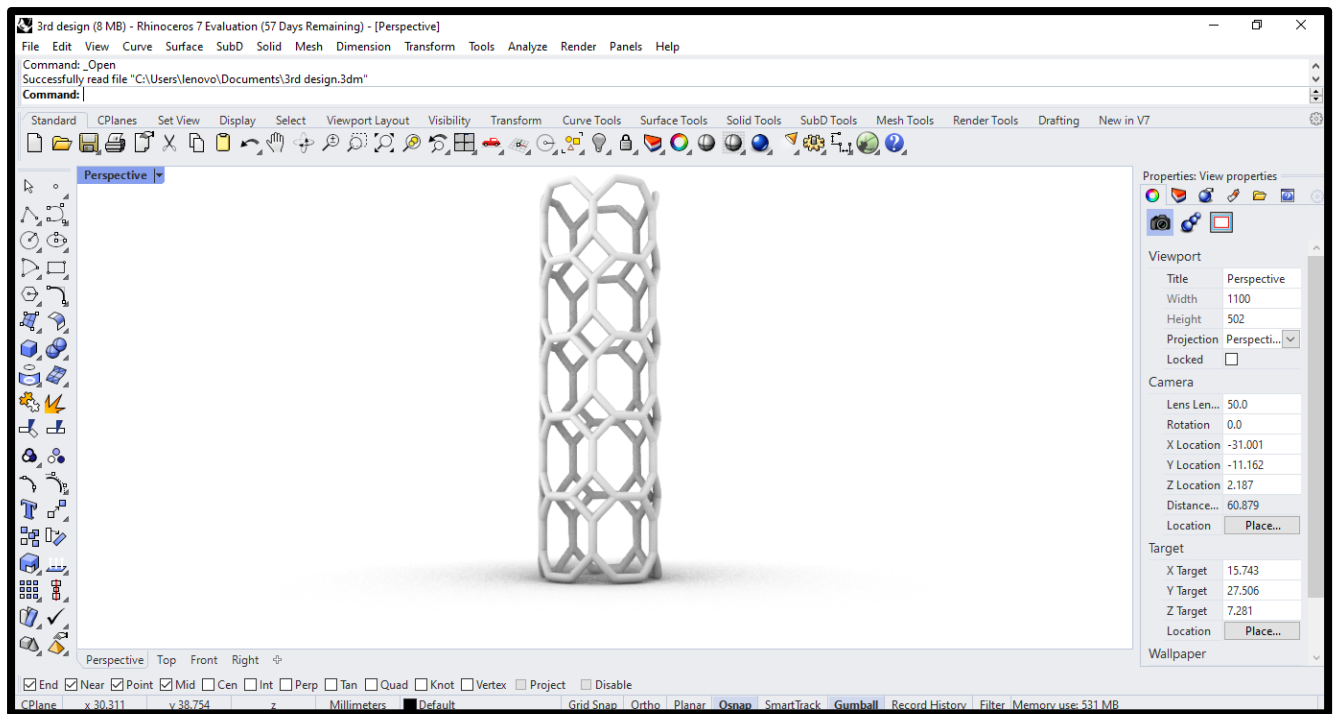


Figure 5.9: Design 2- Diamond shaped cell -perspective view

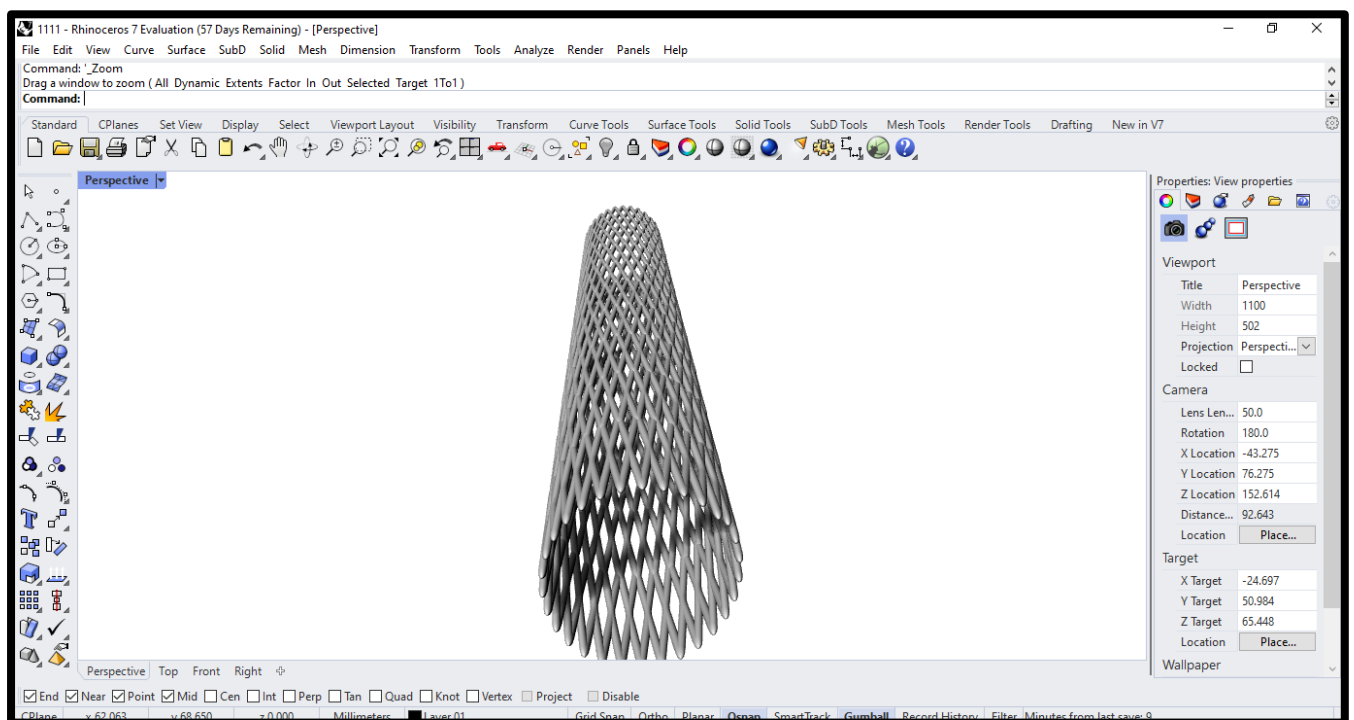


Figure 5.10: Design 2- Diamond shaped cell -lateral view

5.7 TESTING SOFTWARE RESULTS

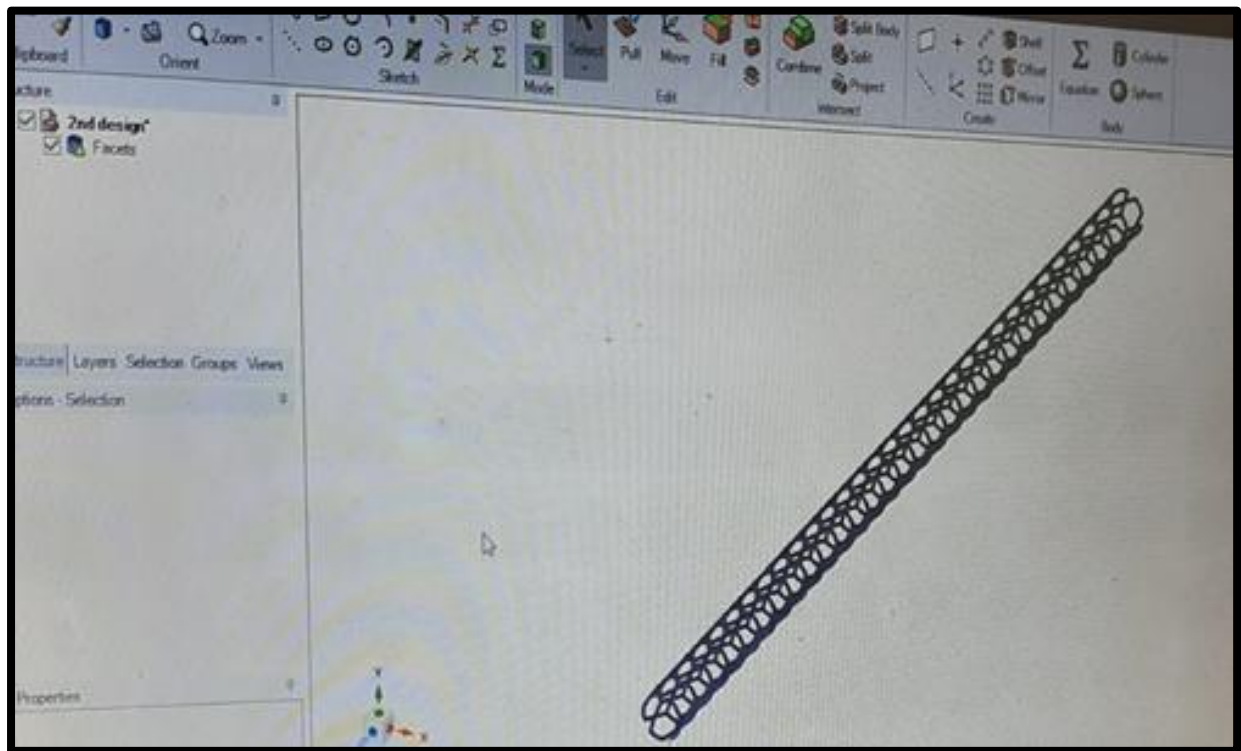


Figure 5.11: Ansys Testing-Stage 1



Figure 5.12: Ansys Testing-Stage 2

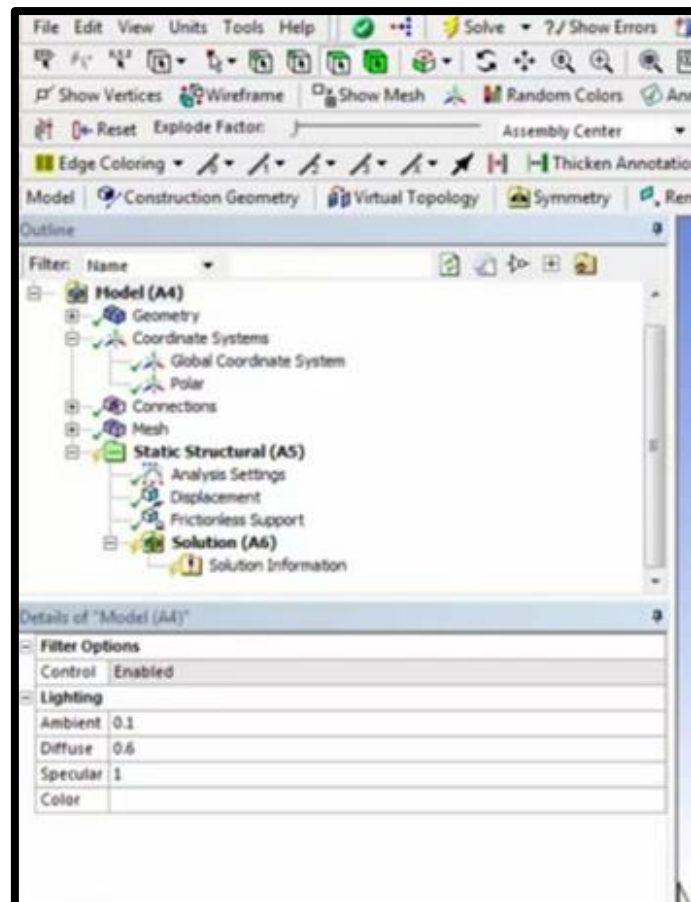


Figure 5.13: Ansys Testing-Stage 3

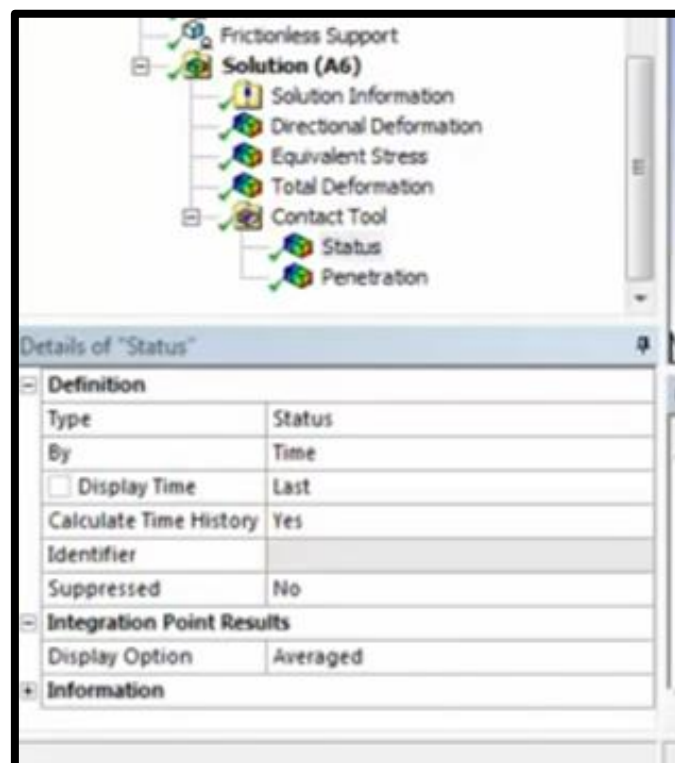


Figure 5.14: Ansys Testing-Completed

5.7 PRINTING

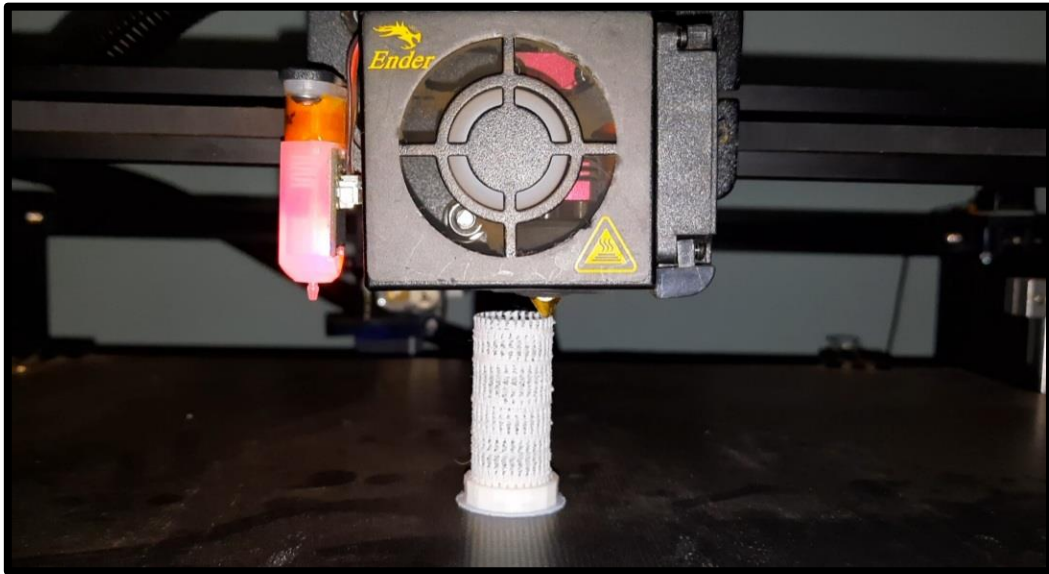
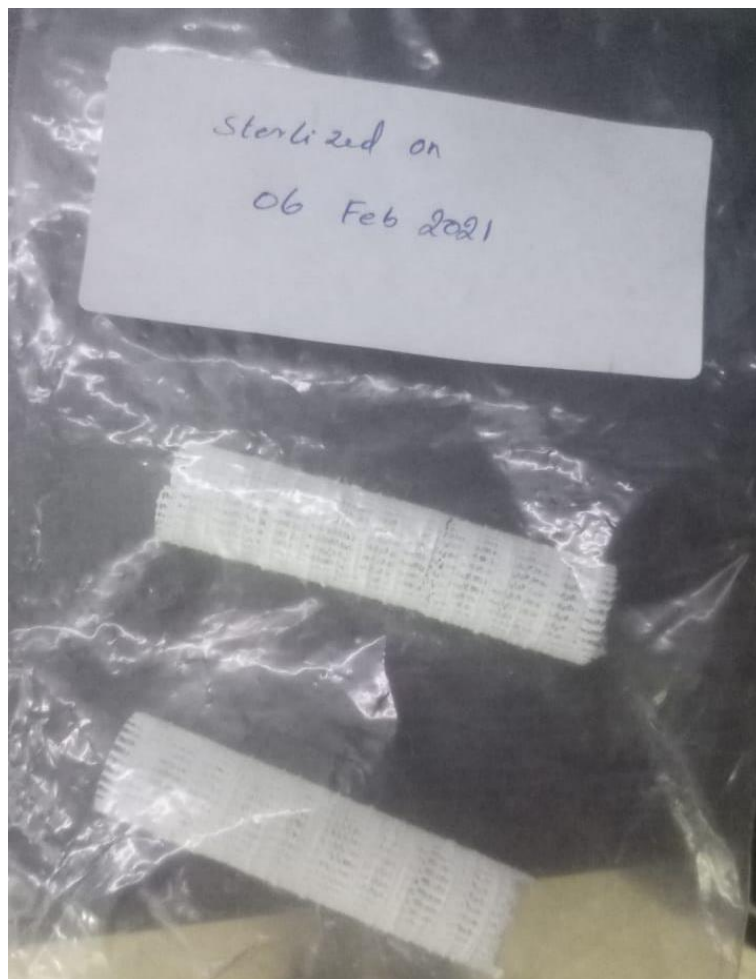


Figure 5.15: FDM Printer printing the final prototype

5.8 PROTOTYPE



CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 CONCLUSION

- Due to a very high mortality rate caused by Pulmonary diseases worldwide, and a promising approach of stent technology, researchers and clinicians are paying great attention to develop new materials, methods, and solutions in order to improve the clinical outcome of currently existing stent types, aiming at more safety for patients, and a higher success rate of Pulmonary treatments. Different stent fabrication technologies, especially those related to coated, bioresorbable, and drug-eluting stents, have been considered in the context of this review paper. [15]
- 3D Printing is distinguished from traditional manufacturing technologies by its ability to handle complex shapes with great design flexibility. This feature makes the 3D printing techniques particularly suitable to produce customized components. In fact, the production of custom-made devices concerns the realization of products suitable to the specific needs of the customer and a low-cost method of manufacturing even a single piece with complex geometries (notoriously a critical aspect for traditional technology). [31]
- This Project highlights the importance of additive manufacturing using 3D printing technology which makes the stent platform quite easy to fabricate. Stents are complicated support structure/Bridges which should meet basic design and size of every individual to avoid rejection and to increase the quality of life. [15]

6.2 FUTURE PERSPECTIVE

Despite the revolutionary role of pulmonary stents in terms of clinical outcomes in interventional pulmonology, complications associated with stent implantation have remained a major problem. Many studies have been published as the treatment method of choice for stent design to address the limitations. Stent design with

multiple materials as well as in combination of materials needed to be simulated to understand the most viable element that can be used for synthesis and also to identify the best possible design which are highly stable. These reported treatments can be categorized into the main list which includes the following attempts: Surface modification with improved polymer coating materials, nanocomposite materials, and tissue engineering- contributed strategy to improve surface properties. There are also affairs to improve the stent backbone like brand new covered stents, polymer-free stents, brand new bioresorbable, and biodegradable materials. To take advantage of biodegradable polymer-based stents, new technologies are being developed. Biomolecule-decorated polymeric surfaces in association with nano-devised techniques would be the most common strategy for future. Unleashing the potential of additive manufacturing will surely open the door to new era of stent technology.^[21]

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